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NASA TN D-1201

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TECHNICAL NOTE

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A PRELIMINARY PILOTED SIMULATOR AND FLIGHT STUDY OF HEIGHT CONTROL REQUIREMENTS FOR VTOL AIRCRAFT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON February 1962

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A PRELIMINARY PILOTED SIMULATOR AND FLIGHT STUDY OF HEIGHT CONTROL REQUIREMENTS FOR VTOL AIRCRAFT

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SUMMARY

A fixed-base piloted flight simulator was used in a preliminary investigation of requirements for VTOL aircraft altitude control. Pilot opinion ratings were used to determine the relationships of control sensitivity, and control power to damping for both normal flight and augmentation failure conditions. These results suggest that to assure satisfactory control characteristics, control power should be capable of producing at least 1.2 G upward acceleration for normal flight and at least 1.05 G for the augmentation failure flight condition. A minimum damping level is about -0.35 per second for normal flight. Flight results obtained with three VTOL aircraft were in reasonable agreement with the simulator data. The influence of control response time constant and ground effect in shifting basic pilot opinion boundaries was also investigated on the simulator. Control response time constant restricts the control boundaries, particularly in the case where high control power and low damping levels or both exist. Introduction of positive ground effect characteristics into the height control system resulted in a marked improvement in pilot-opinion ratings. However, it was found that additional damping was required to cope with the oscillatory hovering behavior induced at levels of control power above 1.2 G. Negative ground effect was responsible for a rapid deterioration in height controllability; excessive sink rates were developed when negative ground effect was combined with low control power.

INTRODUCTION

Reference 1 noted the need for investigations of the requirements for pilot control of height of VTOL aircraft in the presence of the ground and pointed out that the direct effects of control power, control sensitivity, and damping should be determined as well as such influencing factors as ground effect, visibility, control response, and thrust margin. Reference 2 presents a study of the effects of control sensitivity and velocity damping on the height control characteristics conducted using a fixed-base simulator equipped with a sophisticated visual presentation.

The present simulator study was undertaken to investigate the relationships of control sensitivity and control power to damping and to correlate the results with flight test results as well as to investigate further the limitations imposed on these relationships by two of the above characteristics, ground effect and control response time constant. A fixed-base piloted simulator of elementary design was utilized to provide a quick "first look" into these problems. Four NASA research pilots, with varying degrees of VTOL flight experience, participated in the tests.

Control sensitivity requirements were first determined, thus establishing a near optimum value for use in the control power tests. Basic pilot opinion boundaries on the control-power damping plane were mapped. Finally, the influence of control response time constant and ground effect was investigated. Although stored energy is considered to be an important characteristic of height control systems employing rotor components, it was not treated in this study.

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EQUIPMENT

The tests were conducted through the use of the fixed-base piloted flight simulator shown in figure 1. It was decided to provide the pilot with only the essential components with which to evaluate height control performance. The twofold purpose behind this decision was to minimize analog computer mechanization and to enable the pilot to concentrate on vehicle visual motion cues as a primary means for basing pilot opinion.

The pilot was situated approximately 3 feet in front of a 21-inch cathode ray tube (C. R. T.). A height controller of the collective pitch type and operated by the left hand was mounted on a chair next to the pilot's seat. Controller friction was adjustable to pilot comfort, and linear controller gain was used throughout the tests. Total controller travel was adjustable to a maximum value of 10 inches in order to vary control power and sensitivity. Height controller displacements were measured along the arc described by the movement of the center of the hand grip.

Performance tests with a throttle quadrant-type height controller were not included in the present study. Both this type and the collective pitch-type controllers were evaluated in reference 2, and it was concluded therein that no significant differences between the requirements for the two controllers were indicated.

Figure 2 is a reproduction of the pilot's display as seen on the face of the C. R. T. A representative type VTOL vehicle (as seen from the rear) is fixed to the face and a horizontal line, capable of a 10-inch vertical displacement, depicts the ground. An altitude scale is also provided for reference. Control sensitivity and control power tests were conducted with a C. R. T. altitude scale of 1 inch=10 feet; the scale was reduced to 1 inch=5 feet (as shown in the figure) for the remainder of the tests.

The function of the analog computer in the simulation is shown in the block diagram of figure 3. The pilot's controller displacements, acting through a linear gain, command vertical acceleration. The acceleration command signal is further modified by a first-order time delay circuit to approximate engine response and control lag characteristics. Vehicle damping is furnished by feeding back a velocity term. The resultant vehicle acceleration signal is integrated twice to provide the altitude information on the visual display. Ground effect was approximated by a linear function of altitude to a maximum of 20 feet as defined in figure 4. The augmentation of vertical acceleration, to represent ground effect, was added to the vehicle lifting system acceleration as shown in the block diagram of figure 3.

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TESTS

Four NASA research pilots participated in the tests. The Cooper Pilot Opinion Rating System, as reproduced in table I, was used to rate the control characteristics. (For more details concerning this system see ref. 3.) During the tests, the pilot's task was to execute a series of upward and downward height changes as rapidly as possible between two established altitudes with a minimum of "overshoot." It should be emphasized here that the pilot's task involved vertical translation only. The height changes averaged between 20 and 40 feet, and all tests were conducted in gust-free air.

A limited number of flight tests were conducted to provide data for correlation with simulator results. Two helicopters (H-23C and HU-1) and a deflected jet VTOL vehicle (X-14) were used. The pilot's task and the flying conditions were held as close as possible to those described above; that is, flights were conducted during gust-free periods and above ground effect altitudes.

Control sensitivity and velocity damping requirements were first mapped. A near optimum value of control sensitivity was used in establishing the requirements for variations in control power and damping, neglecting the effect of control system time constant and the influence of the ground. Four selected combinations of control power and damping were used to obtain a first look at variable time constant and ground effect characteristics. The control boundary shift due to a combination of the above two factors was not investigated.

RESULTS AND DISCUSSION

Control Sensitivity

The results of the control sensitivity evaluation are presented in figure 5. Throughout this part of the investigation the maximum control power was arbitrarily set at 16.1 ft/sec^2 downward (1/2 G) and 100 ft/sec^2

(3.11 G) upward in order to minimize the influence of limiting maximum upward control power. Ground effect and control response time constant were not included during these tests. Control sensitivity is defined in terms of acceleration change per unit control displacement (ft/sec^2/in.). Velocity damping is defined in terms of acceleration divided by velocity (1/sec). While negative damping (positive values of velocity damping) is not ordinarily encountered in physical situations, this region was investigated in order to clearly specify the "unsatisfactory" boundary.

The 3-1/2 and 6-1/2 pilot ratings shown are of particular interest because they establish the boundaries between the "satisfactory," "unsatisfactory," and "unacceptable" pilot opinion regions. With reference to A
the description column of table I, it is reasonable to specify that a 5
VTOL vehicle height control system fall within the "satisfactory" area, 7
regardless of the number of artificial augmentation devices necessary so 7
long as failure of these devices does not result in an "unacceptable" control rating. Since the "unacceptable" region lies almost entirely within the negative damping area, figure 5 indicates that pilots are willing to accept a control system with little or no damping in an emergency (augmentation failure) situation so long as the control sensitivity exceeds a minimum value of about 2.5 ft/sec^2/in. (0.08 G/in.). Furthermore, tests indicate that vehicles designed to operate anywhere within the "satisfactory" area with a control sensitivity in excess of this minimum are assured of at least operation in the "acceptable" region in the event of complete loss of artificial vertical damping. A portion of 3-1/2 boundary, as determined in reference 2, is presented for comparison.

Pilots progressively downgraded the controllability as control sensitivity was both increased and decreased from a near optimum value of about 10 ft/sec^2/in. This value represents a best balance between overcontrolling of the vehicle, due to excessive control sensitivity, and sluggish response, due to insufficient control power. (Maximum upward control power is a limiting factor in the latter case because of the combination of low sensitivity and maximum controller displacement.)

The approximate values of control sensitivity and velocity damping, as determined by flight tests for the H-23C and HU-1 helicopters, are plotted for comparison. The average pilot rating is also indicated. It can be seen that both helicopters not only fall within the "satisfactory" region, but exhibit control sensitivities slightly in excess of the 2.5 ft/sec^2/in. minimum value discussed above. The position of the points for the flight articles indicate a reasonable agreement between the pilot ratings as determined from flight and the simulator tests, thus adding credence to the results of the simulator evaluations.

Control Power

The results of the maximum control power tests are depicted in figure 6. Shown here is the variation, with velocity damping, of the maximum upward control power (in units of G where 1 G represents no vertical acceleration) required to realize a given pilot rating. The variation of maximum downward control power (or in effect the minimum vertical thrust available) was not studied since it was felt the type of vehicles being considered could always reduce vertical thrust to a negligible value in terms of weight (no buoyancy). It was reasoned that increasing downward control power would increase demands on upward control power; downward control power was held fixed, therefore, at a logical maximum representing zero upward thrust or 0 G. All control power tests were conducted at a near-optimum value of control sensitivity of 10 ft/sec^2/in. Negative values of damping were not investigated. Values of upward control power above 1.5 were considered academic and were not studied.

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Examination of the 3-1/2 boundary indicates that in order to assure "satisfactory" control characteristics (within the range of control power and damping investigated) maximum control power out of ground effect should be capable of producing at least 1.2 G upward acceleration. In the pilots' opinions, this value is sufficient to arrest a reasonable rate of sink and stabilize at a selected altitude. Increasing the maximum control power from the 1.2 G level to about 1.4 G greatly reduces the amount of damping required. A minimum damping level requirement of -0.35 per second exists at the largest control power investigated (1.5 G).

The 6-1/2 boundary indicates a minimum acceptable control power (for emergency conditions) of 1.05 G. Vehicles with damping of less than -0.4 per second will require somewhat higher values of control power. It can be seen that with maximum control power exceeding an approximate value of 1.16 G, no vertical damping is indicated to be required to remain in the "acceptable but unsatisfactory" region.

It is interesting to note that operation in the "satisfactory" region insures resultant operation within the region bounded by the 6-1/2 boundary in the event of loss of the artificial damping system. This factor is particularly important when considering height control requirements for pure turbojet vehicles which inherently exhibit low vertical damping characteristics.

Maximum control power and damping values for the X-14, H-23C and HU-1 aircraft are plotted in figure 6 for comparison purposes. It should be noted that these aircraft do not have the control sensitivity used for the simulation (see fig. 5). Average pilot opinion ratings for each vehicle are included. Pilot ratings obtained in flight agree quite well with the simulator data. The low damping and control power characteristics of the X-14 put it in the "unacceptable" region. The high damping and stored energy, which characterizes the two helicopter rotor systems, put them well into the "satisfactory" area. Stored rotor energy, in the form of angular momentum, is available to the pilot for height changes requiring peak upward accelerations. Utilization of this additional energy accounts for a great deal of the higher levels of maximum control power associated with rotary wing vehicles. The HU-1 is powered by a gas turbine engine with a self-governing RPM rotor. In addition to increasing the maximum upward control power, this combination relieves the pilot of the added task of having to coordinate throttle and collective pitch in order to maintain rotor RPM within limits. The vehicle is thus more pleasant to fly, and the pilot can take maximum advantage of stored rotor energy through the use of rapid collective-pitch control applications.

Time Constant

The purpose of this part of the investigation was to obtain a "first look" into the effect on pilot rating of the addition of height control time constant. Therefore emphasis should be placed on the rate of change of pilot rating with increasing time constant rather than on absolute values. Vehicle height control system time lag, created by engine thrust response characteristics and other control motion lags or both, was approximated by a first order time delay (i.e., time to reach 63 percent of the steady-state value).

Four combinations of maximum upward control power and velocity damping were selected for the control time constant and ground effect evaluations, two each in the "satisfactory" and "unsatisfactory" regions. (The points have been noted on fig. 6.) Differences observed in the averaged pilot ratings at zero time constant in figure 7 (and out of ground effect in figure 8) as compared to figure 6 are due to daily "scatter" in the data points among the pilots participating in the tests.

Results of the time constant evaluation are presented in figure 7. To facilitate discussion, the four curves are identified by Roman numerals I through IV. Curve I represents a combination of medium control power (1.2 G) and high damping (-1.0). In curve II the damping was reduced to -0.125 while control power was held at the same level. Curves III and IV represent conditions with fixed damping (-0.5) in combination with two extremes in control power; 1.4 G and 1.06 G, respectively.

A comparison of curves I and II indicates the importance of adequate damping levels for height control systems exhibiting finite levels of time lag. Pilots were able to cope with a time constant of 1 second resulting in a pilot rating increase of only 1-1/2 (Curve I) while for the low damping case the increase in pilot rating was 3-1/2 because of the combined effects of the overcontrolling tendency at low damping and the time constant.

Curves III and IV illustrate the effects of time constant change on two different maximum upward control power levels. Pilot rating was insensitive to time constant increase up to about 0.2 second for the low control power case (Curve IV). For the high control power case, an increase in time constant caused the pilot to overcontrol, thus pilot rating was greatly influenced by time constant.

It might be well at this point to discuss briefly a few of the VTOL design considerations which were made evident during this portion of the tests. In cases where rather long height control time constant is a necessary characteristic of the vehicle, such as can be the case for some turbojet types, close attention must be paid to assure that damping is sufficient for operation in the "satisfactory" range. If control powers above 1.2 G are considered, damping requirements must be adjusted to the level of time constant. For designs with high control power and low levels of damping artificial damper failure could result in "unacceptable" operation.

Ground Effect

Results of the ground effect tests are summarized in figure 8. The curves are numbered I through IV as in the preceding figure. The data show pilot rating as a function of the ratio of maximum upward control power in and out of ground effect. (See fig. 4.) A ratio value of 1.0 divides the plot into two regions; positive ground effect to the right and negative ground effect to the left.

Increasing ground effect up to a value of approximately 1.2 tends to improve height control handling qualities. The beneficial influence of positive ground effect is quite pronounced in the case where only marginal levels of control power away from the ground are obtainable (Curve IV). On the other hand, a comparison of curves III and IV indicates that the degree of improvement at the higher control powers is not so pronounced.

Curves II and IV reflex upward above a ground effect level of about 1.2, indicating a deterioration in pilot rating. Attempts at hovering within the influence of positive ground effect produced a vertical oscillatory motion typified by a mass suspended on the end of a spring. If damping is low, a condition is reached where the combined effects of low damping, greatly augmented control power, and induced "spring effect" result in overcontrolling. With high damping and positive ground effect (Curve I), the height controller becomes a position control. For a particular controller setting an equilibrium height is reached about which the vehicle will show positive stability until the controller is displaced. The relatively slight reflex in curve IV is probably due to the inability of the pilot to cope with the oscillatory mode using low control power.

The rapid decline of pilot rating in negative ground effect for all four conditions is quite pronounced. The steep slope of curve IV illustrates how marginally low levels of control power further aggravate the characteristic sinking divergence associated with negative ground effect. In this particular case it should be pointed out that at a ground effect level of approximately 0.94, maximum control power lift equals weight. This condition could induce dangerous settling and possible catastrophic airframe failure.

VTOL vehicle design must provide adequate levels of damping and control power to insure "satisfactory" operation within ground proximity; that is, sufficient damping to handle positive ground effect or enough control power to cope with negative ground effect.

Typical scatter of the data obtained from the three pilots who participated in the time constant and ground effect tests is represented in figures 9 and 10, respectively. The initial conditions of curve I were used for control power and damping values in both plots. In general, the deviations in pilot rating from the average were less than one (fig. 9). A factor which contributed to the scatter is the elementary nature of the pilot's display. Scales used in some cases, to depict altitude on the C. R. T., tended to mask the pilot's perception of unrealistically large vertical velocities. Another factor lies in the lack of acceleration cues (fixed-base cockpit).

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CONCLUSIONS

Hovering height control boundaries for both control sensitivity and control power have been evaluated with a fixed-base piloted flight simulator. The following conclusions have been made as a result of this investigation:

1. Optimum height control system sensitivity lies approximately between 7 and 12 ft/sec^2/in.

2. An upward acceleration of 1.2 G was the lowest value of control power (within the range of damping investigated) for "satisfactory" control characteristics. The level for minimum acceptable safe operation was 1.05 G.

3. Control sensitivity and damping as well as control power and damping relationships indicate that vehicles designed to operate within the "satisfactory" area are assured of operation in at least the acceptable region in the event of complete loss of artificial vertical damping.

4. Pilot opinion ratings deteriorate rapidly with increasing control response time constant, particularly when low damping levels exist.

5. Positive ground effect generally improves basic height control handling qualities, but additional damping is required to cope with the oscillatory hovering behavior induced at levels of control power above 1.2 G.

6. Negative ground effect causes a rapid deterioration in controllability. When combined with low control power, negative ground effect can cause dangerously excessive sink rates.

7. Simulator results correlate reasonably well with the limited amount of flight data obtained.

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Moffett Field, Calif., Oct. 27, 1961

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TABLE I.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter

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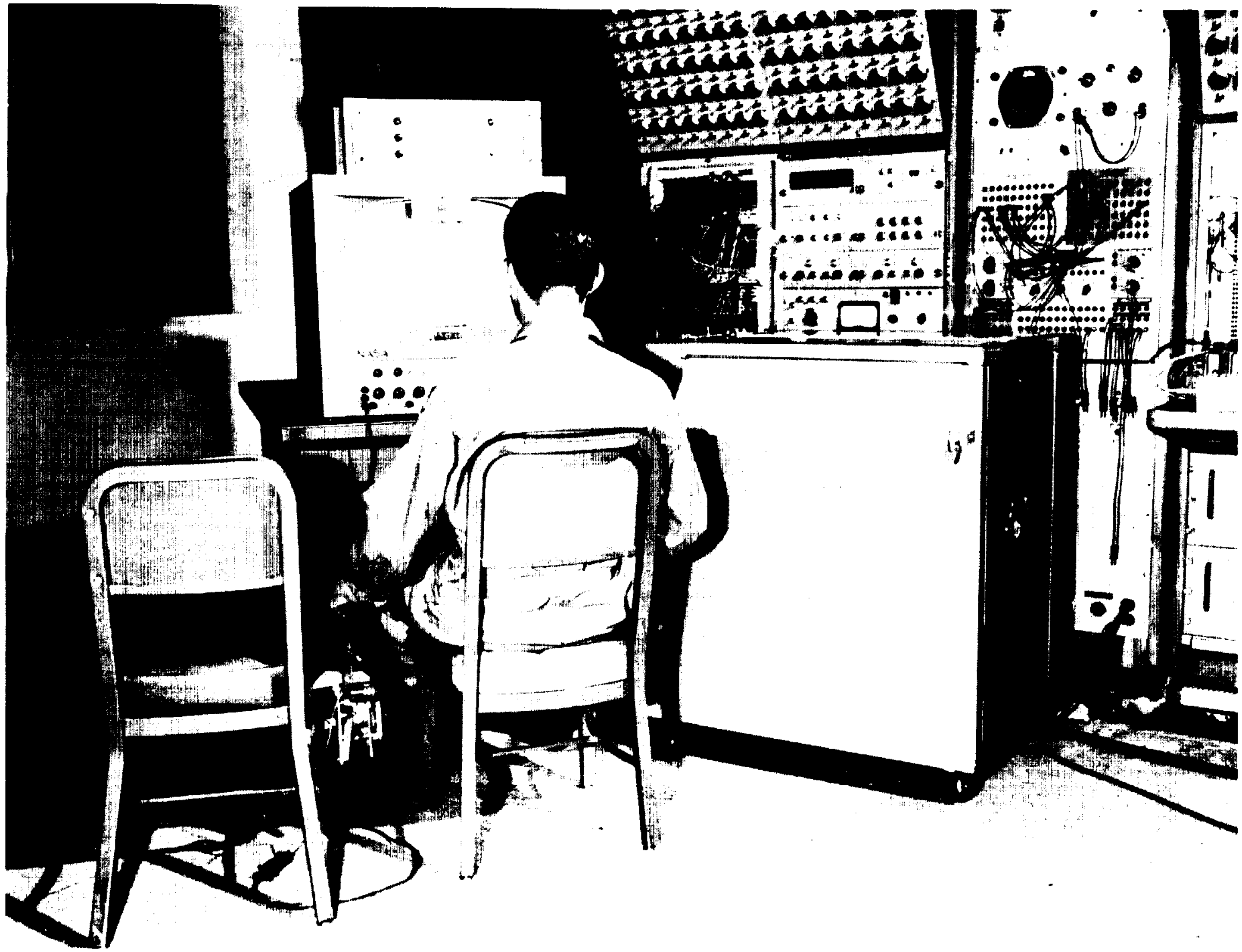

Figure 1.- General view of simulator.

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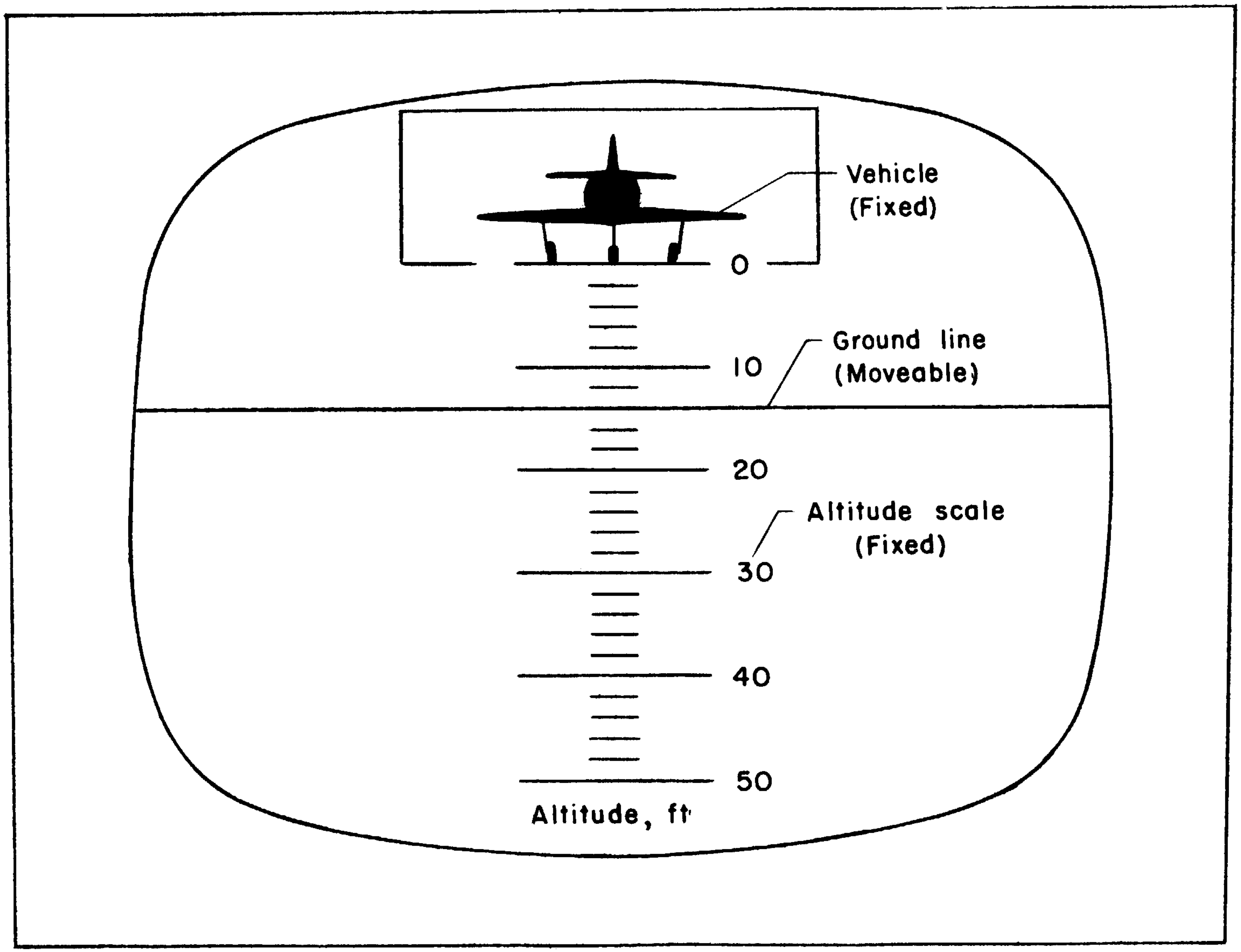

Figure 2.- View of pilot's visual display.

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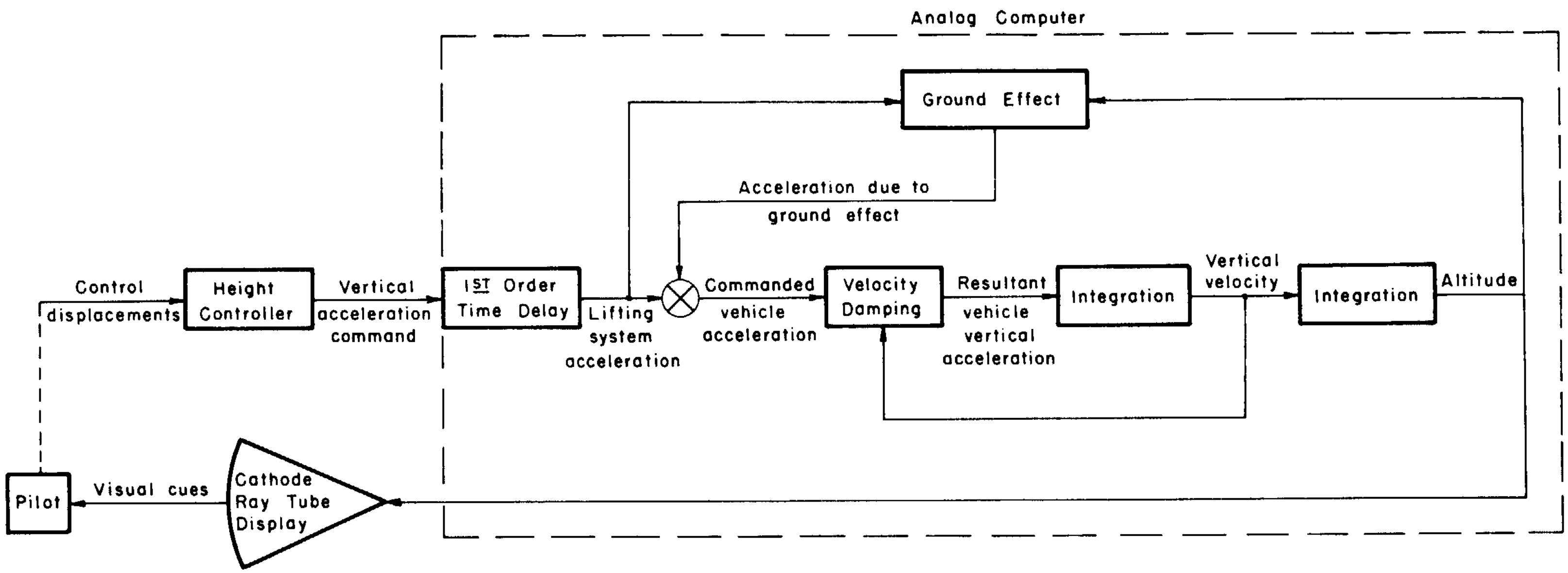

Figure 3.- Block diagram of simulator.

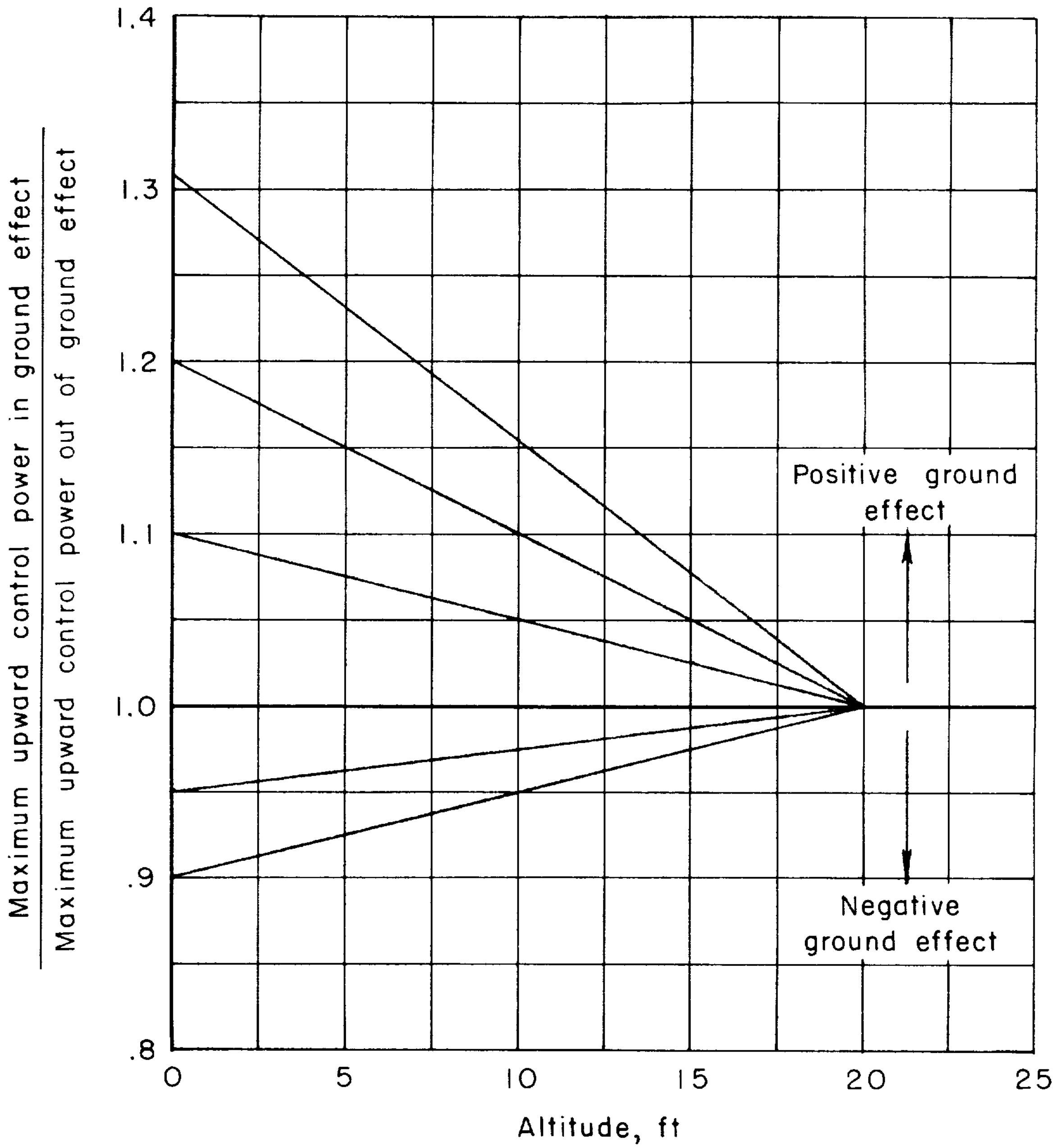

Figure 4.- Five variations in levels of ground effect used.

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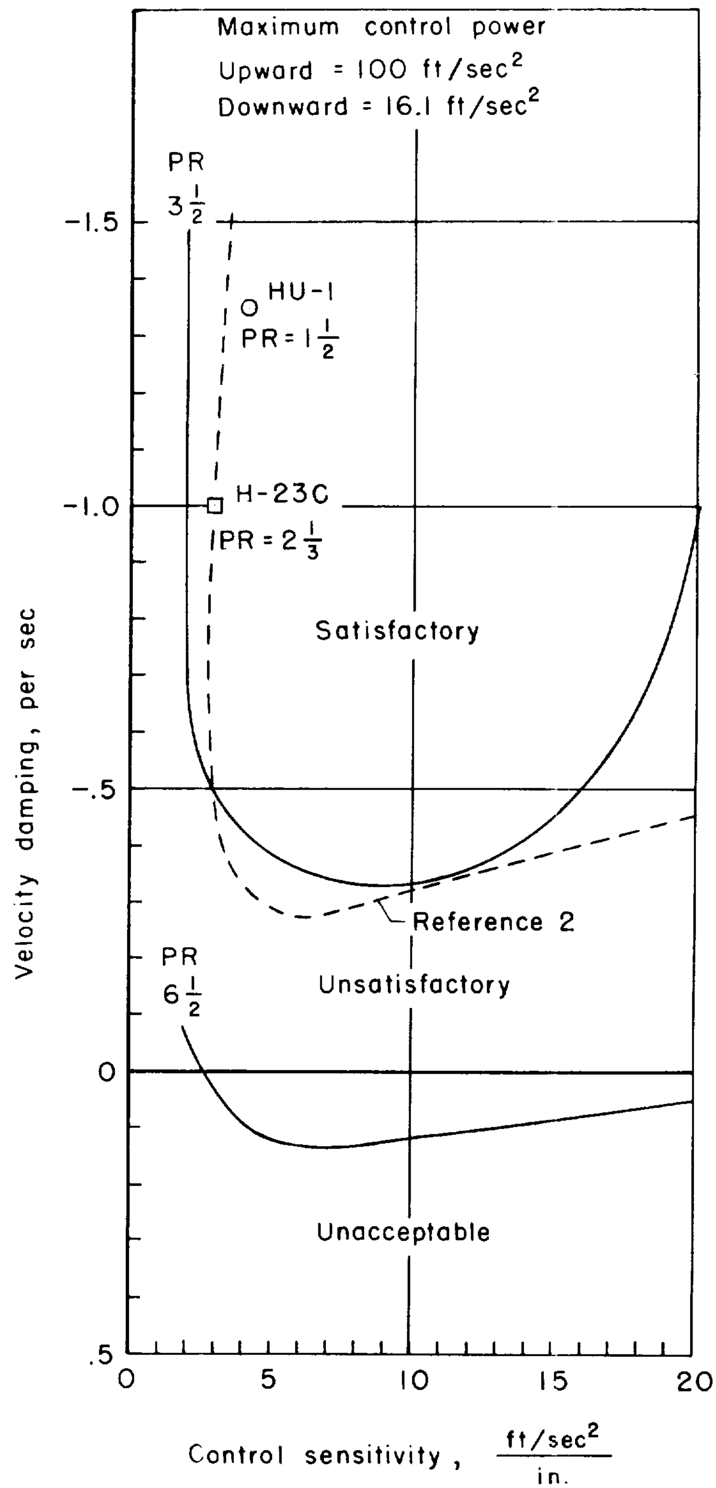

Figure 5.- Control sensitivity boundaries out of ground effect and with control system time constant of zero.

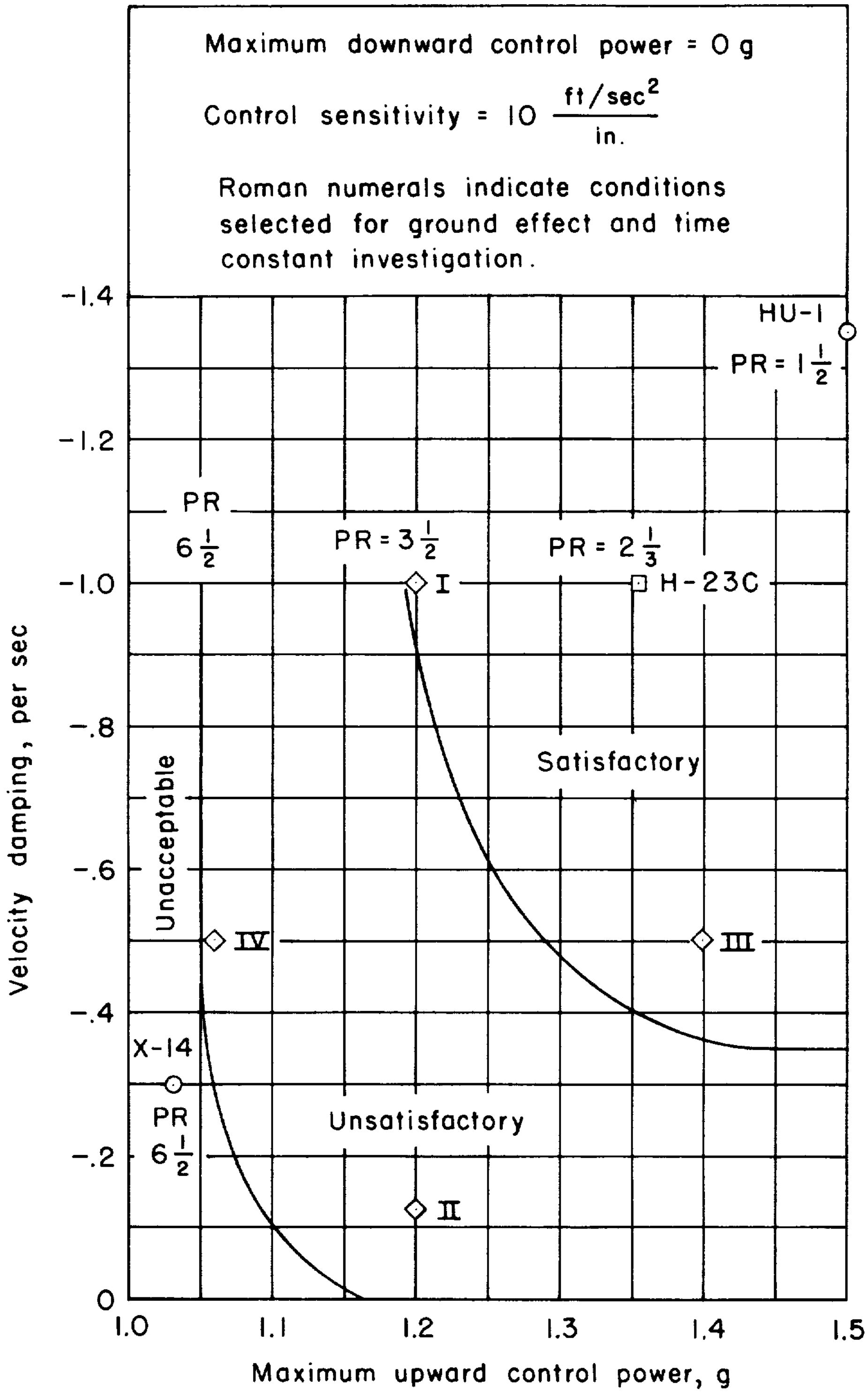

Figure 6.- Maximum control power boundaries out of ground effect and with control system time constant of zero.

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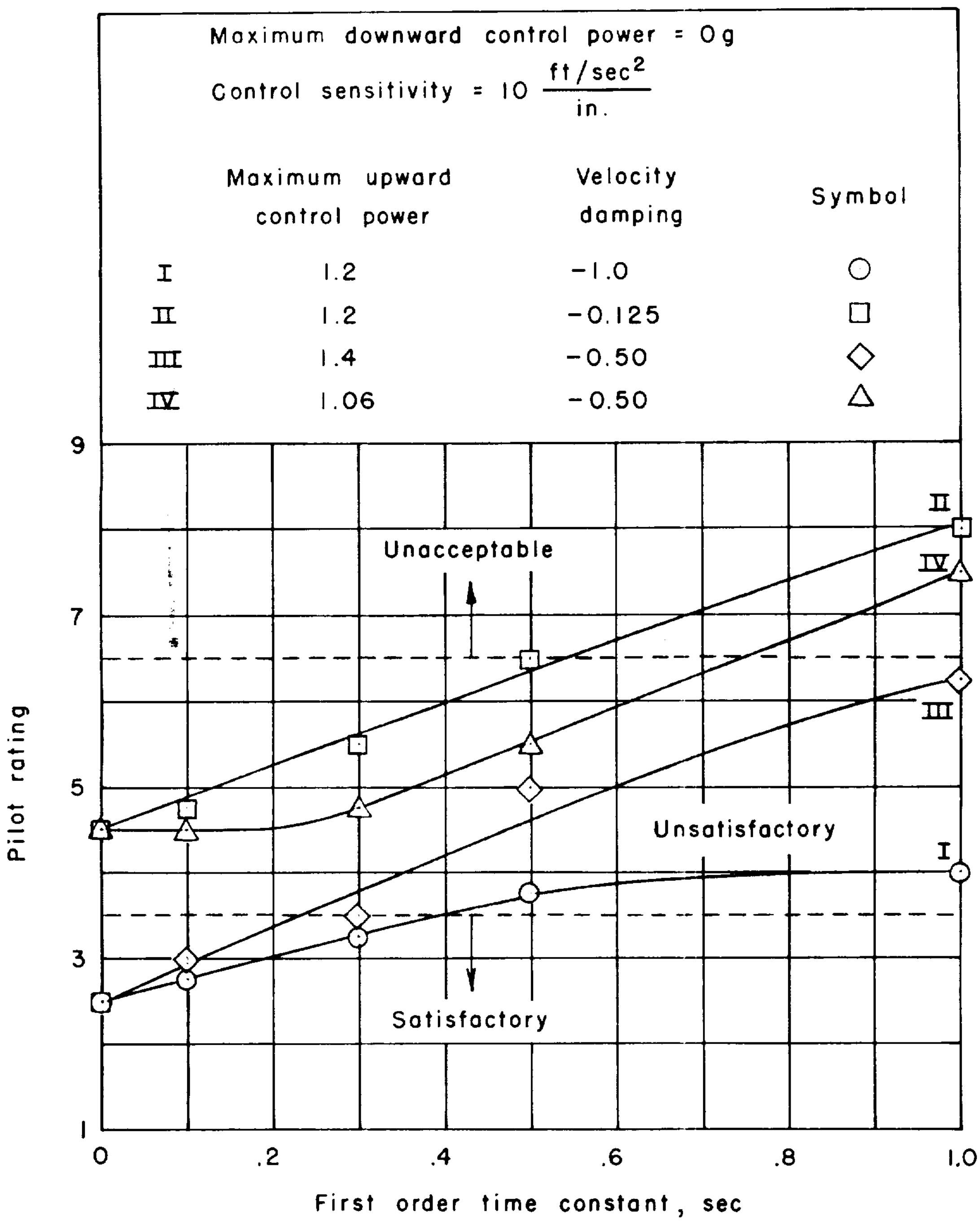

Figure 7.- Pilot rating shift due to control system time constant out of ground effect.

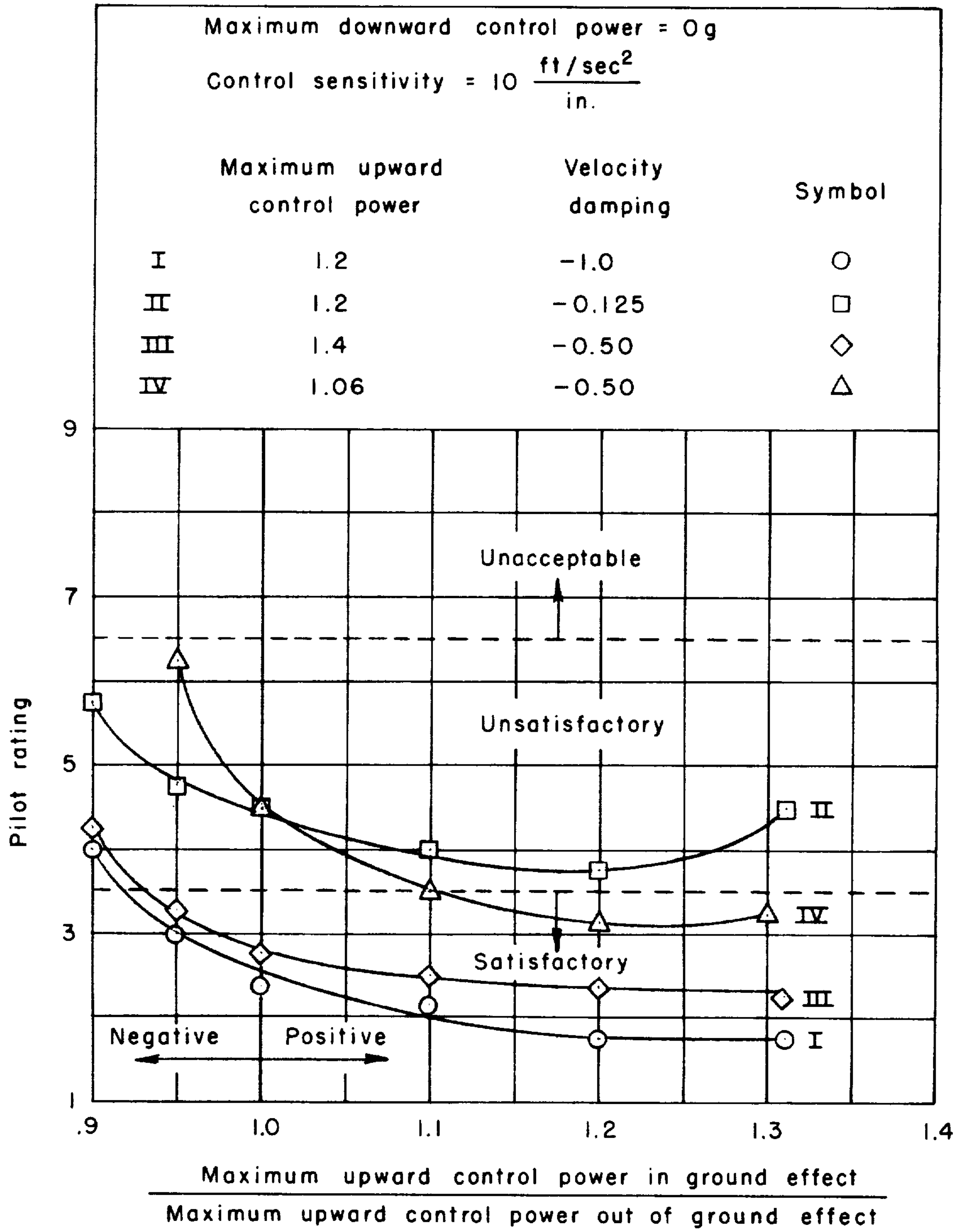

Figure 8.- Pilot rating shift due to ground effect and with control system time constant of zero.

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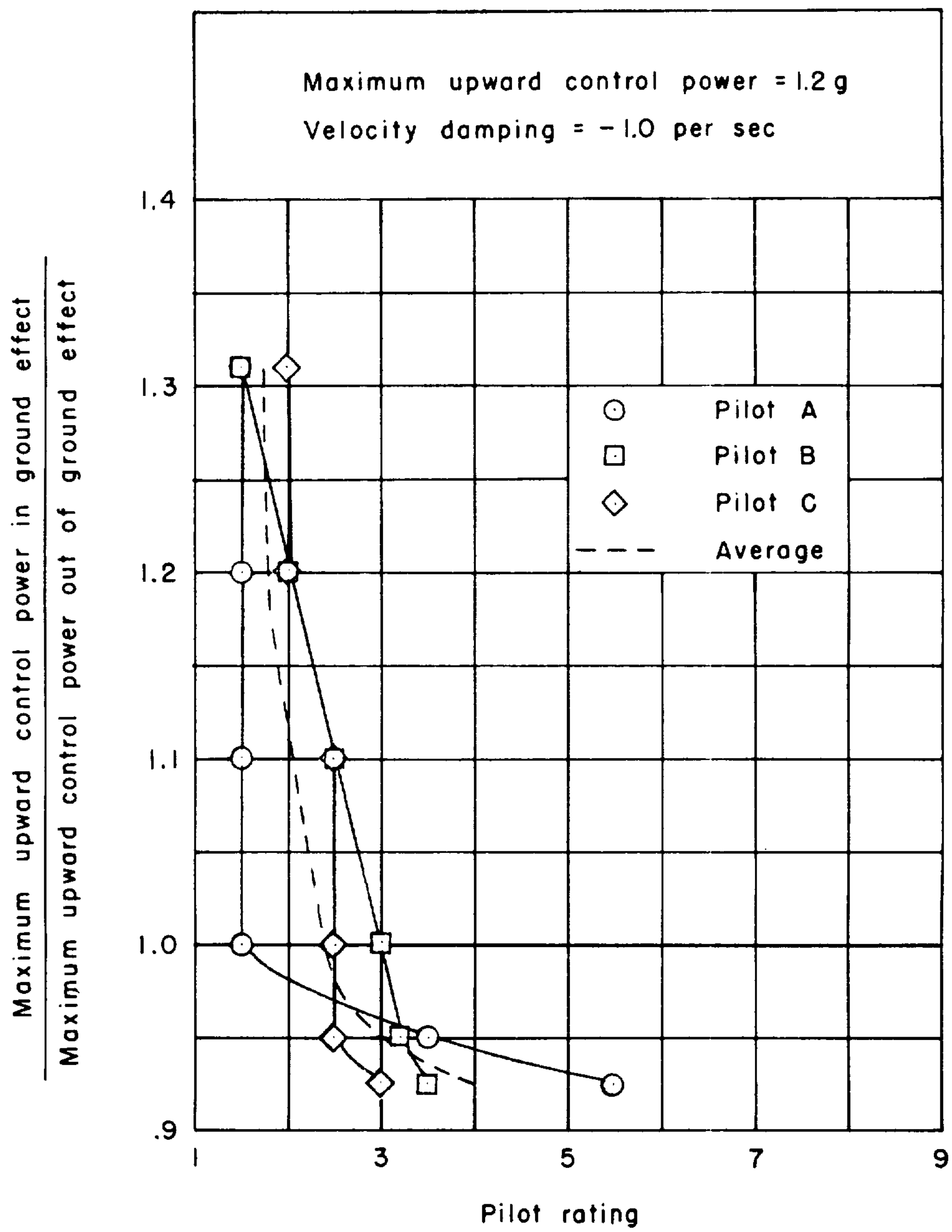

Figure 9.- Typical pilot ratings of ground effect and with control system time constant of zero.

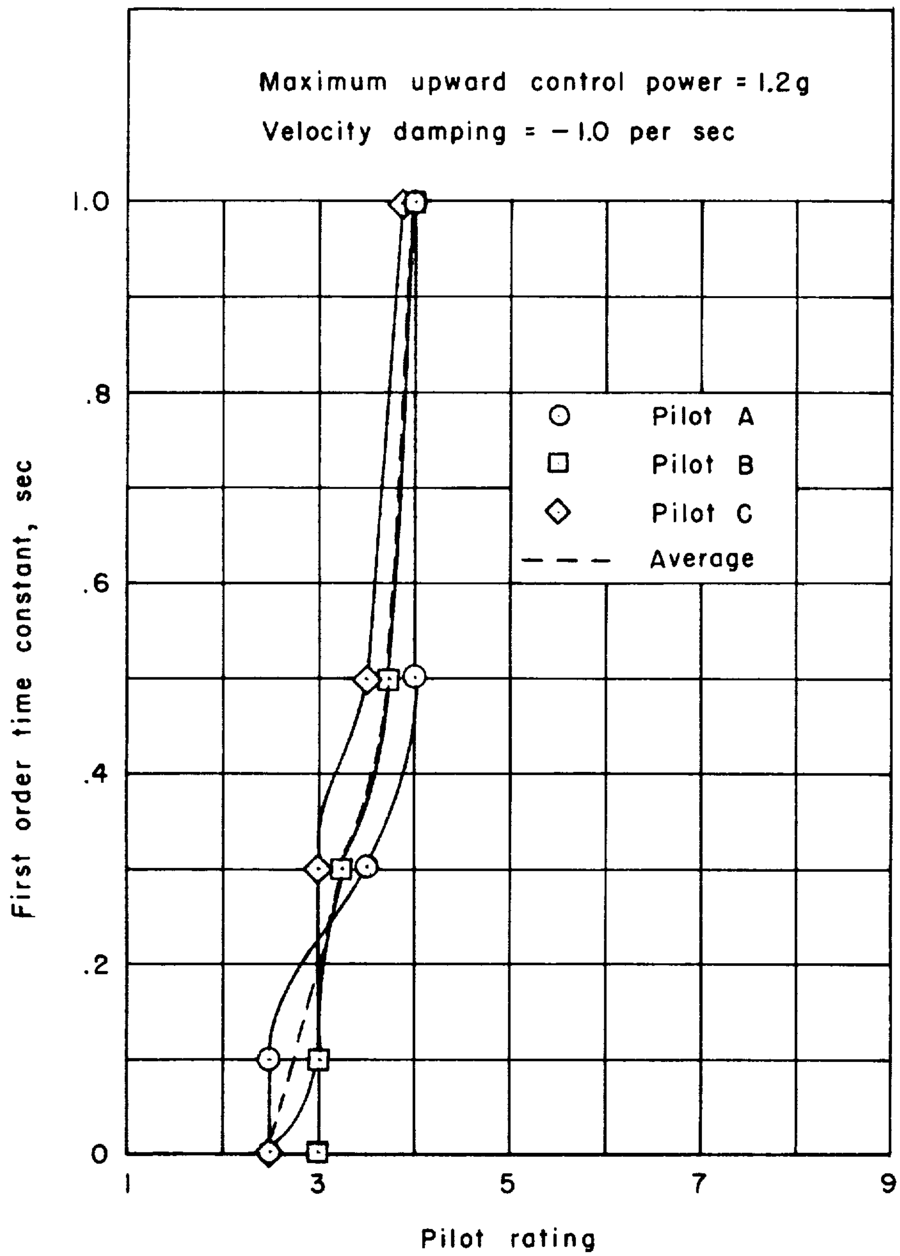

Figure 10.- Typical pilot ratings of control system response time constant out of ground effect.

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